There is potential for pumped hydro energy storage in New Zealand

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Abstract

The decarbonisation of New Zealand's energy system will increase demand for electricity at the same time as fossil fuelled generation is phased out. Maintaining balance in the power system will become increasingly difficult as more variable generation is integrated and it is unlikely that the existing generation portfolio, with any additional generation, and demand side management will allow sufficient control. It will be necessary to increase energy storage and generation capacity. Pump Hydro Energy Storage (PHES) is the most cost effective mature energy storage technology; comprising 95% of active energy storage worldwide. PHES has relatively low carbon emissions, a high energy storage to investment ratio and long plant lifespans. However, costs and risks are project specific reflecting the range of scheme designs and dependence on geomorphology. Further, the time to develop PHES schemes is long and have environmental and other impact that are complex to assess. There is a lot to be gained from systematic evaluation of resources and optimisation of scheme designs. Here an overview of the technology, summary of previously proposed projects, and results from a search for a variety of scheme types is presented. To support resource evaluation, a GIS based evolutionary algorithm is developed and used to find a quasi-optimal upper reservoir location for a scheme using Lake Roxburgh as the lower reservoir and to identify reservoir locations for a closed loop scheme.

Introduction

Achieving the net zero emissions economy target proposed by the New Zealand government and to be enacted by the Climate Change Response (Zero Carbon) Amendment Bill [1], will require large-scale electrification at the same time as replacing fossil fuelled generation with renewables. It is expected that the increased electricity demand will be met by geothermal, wind and solar power. While geothermal is usually dispatched as baseload, wind and solar have certain levels of unpredictability and variability, hence balancing the power system will become increasingly difficult.

Even though New Zealand has an extensive portfolio of hydro and geothermal power plants it is unlikely there will be sufficient generation available during demand peaks to maintain power system balance without increasing generation and storage capacity. It has been estimated that for New Zealand to achieve 100% renewable generation, given the electricity demand in 2010, would require an additional 1550 MW of peaking generation capacity and 364 GWh of storage [2]. With projected demand growth it has been estimated that the power generation capacity will need to increase by approximately 5000 MW to meet winter evening peaks if the 2050 carbon zero target is to be achieved [3]. This additional generation must not only be available on-demand but also integrate into the existing power system.

New Zealand power system

The power system in New Zealand has been shaped by the need to exploit large hydro resources and convey the energy to distant major load centres. Hydro power provides nearly 60% of all electricity and the large hydro power plants on New Zealand's major rivers (Waikato, Waitaki and Clutha) provide the power system with great strength and reliability. Hydro resources also provide the majority of renewable energy storage, with a large proportion held in lakes Pukakai and Tekapo.

The power system has had few wide spread power outages or shortages, with no system wide black outs since the birth of the grid in 1934 [4]. Arguably much of this strength is due to the reliability and capability of the hydro generation portfolio. However, the greatest risk to New Zealand's power system comes from its reliance on hydro, resulting in a shortage of energy in dry years, as seen in 1992. New Zealand has significant untapped hydro resources [5], however it is unlikely that there will be more large hydro power schemes constructed due to environmental opposition [6]. To ensure that power system stability is maintained, while increasing demand and variable generation will require increasing controllable loads and generation. It is certain that some control will be gained through demand side management, but it is unlikely there will be sufficient flexibility in loads to cover the full requirements [7]. Hence, there is a need to increase generation backed by energy storage.

The need for storage is evident in the installation of the 1MW / 2 MWh battery by Mercury at the Southdown Grid eXit Point (GXP) [8]. While lithium-ion (Li-ion) batteries are "infinitely" scalable and costs are declining, their long term value is uncertain. Life expectancy for Li-ion batteries is relatively short, recycling options are not assured and the energy stored relative to investment is low [9] [10]. Hydrogen energy storage has also recently received a lot of attention in New Zealand, however its economics and maturity are not assured [11]. There is a growing need to examine energy storage options.

Pumped Hydro Energy Storage

Pump Hydro Energy Storage (PHES) works by pumping water from a lower reservoir to an upper reservoir when excess power is available and using this water to generate power when needed. PHES presently accounts for more than 95% of active energy storage worldwide [12] and is considered the only commercially mature power generation storage technology [13, 14]. The economics and environmental impacts of PHES are compared with Lithium Ion batteries (Li-ion), Power to Hydrogen to Power (P2H2P) and Vanadium Redox Flow Batteries (VRFB) in Figure 1. These analyses show that PHES has favourable levelised costs [15], energy stored on invested [16], lifecycle carbon dioxide emissions [17-19] and cycle efficiency [11, 20]. For each metric average values are presented for grid connected facilities with technology specific capacities with a storage size to capacity ratio of 4.5 hours. Real world figures will be project specific and may differ greatly from those presented.

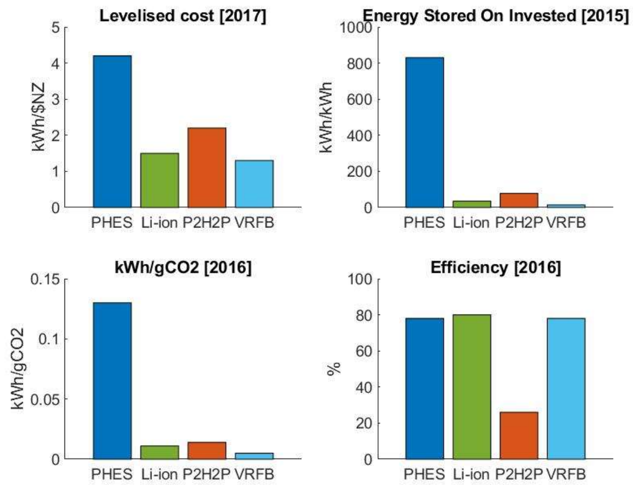

Figure 1 Comparison of PHES with Lithium Ion batteries (Li-ion), Power to Hydrogen to Power (P2H2P) and Vanadium Flow Redox Batteries (VRFB)

PHES schemes vary greatly in size; Bath County is the largest scheme in the world with a capacity of 3GW, whereas El Hierro in the Canaries has a capacity of 11MW. Schemes such as Bath County were built to ensure peak demand is met while allowing nuclear plants with gigawatt capacities to operate at a constant output [21]. In comparison, El Hierro was constructed to provide energy security for a small island. While there is a large range in capacities the economics improve with size [22] with the worldwide mean capacity is 500 MW [23].

The hydraulic efficiency of a PHES scheme is dependent on the difference in height between the reservoirs (the head) and friction losses in turbines and penstocks. The greater the head, the smaller the volume of water that needs to be moved to store a quantity of energy, requiring smaller reservoirs, pump-turbines and penstocks. The head of PHES schemes varies from as high as 1265m (Edolo, Italy), to as low as 70m (Kiev Pumped Storage Plant); generally PHES plants have heads greater than 300m. The distance between reservoirs is important, impacting not only the operational efficiency but also the cost of construction. A reasonable measure for assessing the potential of a PHES scheme is the head to length ratio. As a rule of thumb this ratio should be greater than 0.1 [24].

The efficiency and costs of PHES depend on morphology; with leakage, evaporation, precipitation and inflows requiring consideration with auxiliary components such as reservoir lining, floating solar panels and spillways adding to costs. PHES schemes can have environmental impacts such as extensive littoral zones which may limit project operation and present barriers in the consenting process [25]. Geology has an immediate impact on scheme costs where existing topographic features can be used to lower costs [26], conversely if tunnels and penstocks require extensive support or dams require extensive grouting then budget overruns can be encountered. Consequently PHES costs vary greatly [27].

Table 1 Details of example PHES schemes and schemes proposed in New Zealand

Name	**Date**	**Place / Reference**	**Capacity [MW]**	**Storage [GWh]**	**Head [m]**	**Length [km]**	**H/L**
Bath County	1985	USA	3030	24	400	1.8	0.22
El Hierro	2016	Spain	11	0.6	653	2.4	0.28
Edolo	1985	Italy	1000	53	1265	9.7	0.13
Kiev	1972	Ukraine	235		70	0.5	0.14
Lake Onslow	2006	Bardsley		12000	650	20	0.033
Hawea	2012	Bardsley		211	65	2	0.033
Tekapo	2018	NZ Prod Com					
Stewart Island	2016	Mason		0.000032	75	0.5	0.150

Because of the great diversity in PHES scheme designs it is useful for evaluation purposes to use a classification system. Here four PHES scheme types are detailed in Table 2, Types 1 & 2 are referred to as open-loop schemes, whereas 3 & 4 are off-river or closed loop schemes. Open loop schemes use existing hydrologic resources and can have reduced requirements for construction of dams, but the operation of such a scheme may conflict with existing hydrologic systems and water uses. Closed loop schemes can have less flood control requirements and have greater flexibility in site selection.

Table 2 PHES scheme classification

PHES Scheme type	**Description**
1	Use of existing upper and lower reservoirs
2	Construction of an upper reservoir above an existing water body
3	Use of brown-fields sites (e.g. abandoned mine pits)
4	Construction of off river schemes (e.g. constructing upper and lower reservoirs)

PHES represent large investments and can have long and complex processes for engineering design, consenting and construction. Projects must pass a high threshold before being progressed hence identifying credible options at an early stage is advantageous.

The identification of PHES schemes primarily relies on identifying pairs of water bodies, or locations where reservoirs can be formed, with suitable height differentials. Sites can be identified either through existing knowledge, particularly the case for brown field sites, or by systematic searches. Systematic searches may use databases of existing water bodies for Type 1 scheme development [28], or may use Geographic Information System (GIS).

GIS searches typically focus on finding sites suitable for dry valley or "turkey nest" type dams and can result in the identification of a very large number of sites such as in the "atlas" of 22,000 sites identified in Australia by Blakers et al [29]. The magnitude of the task for identifying sites for Type 4 schemes is outlined by Connolly et al. who applied an algorithm to an area covering a very small part of Ireland [30]. Further, the set of possible PHES schemes expands greatly when the sea is considered for use as a lower reservoir, as is the case for Okinawa Yanbaru [31].

PHES in New Zealand

In 2013 PHES was generally considered by industry representatives to be uneconomic and it was unlikely that any plant would be constructed before 2025 [32]; reflecting this only 4 scheme proposals have been identified in the literature. However, the case for storage has changed significantly in the short period of time since this review was undertaken.

The most significant proposal has been a scheme using Lake Onslow, fed by water from the Clutha River [33, 34]. While this scheme would have a head of 650m and a very large storage capacity, the 20km distance from the Clutha would require an atypical scheme design. However, the purpose of this scheme would be to alleviate New Zealand's dry year risk and it would draw economic value from providing security of supply and seasonal energy balancing.

Another proposed scheme would link lakes Wanaka and Hawea [34, 35], this is of interest as it highlights a potential barrier; the mixing of waters which may not observe Kaitiakitanga. Other PHES schemes that have been identified include using Lake Pukaki or Lake Tekapo as tail pond reservoirs [36], and a small scheme for a 100% renewable electricity system for the remote community of Oban in Stewart Island [37]. While a literature search does not reveal many potential PHES schemes in New Zealand, given the topography and hydrologic resources in New Zealand, the potential for PHES justifies a methodological evaluation.

Type 1 schemes

Searching for Type 1 schemes is straightforward and results from a search based on the NZ Lakes polygons dataset [38] are presented here. The lakes have been filtered to remove those that are in, or border Department of Conservation land. Pairs are identified that would allow storage of at least 100 MWh (assuming an operating range of 10m), have a minimum difference in elevation of 50m and have a head to length ratio greater than 0.66. The search results are presented in Table 3.

Table 3 Results of a Type 1 search for PHES schemes using the NZ Lakes polygons dataset

Lower reservoir	Upper reservoir	Distance [km]	Head [m]	H/L	Storage [GWh]
Wakatipu	Lake Johnson	1.2	91	0.08	0.1
Wakatipu	Lake Luna	4.2	502	0.12	0.8
Wakatipu	Lake Dispute	1.1	160	0.14	0.2
Wakatipu	Lagoon Creek	1.2	116	0.09	0.4
Lake Sumner	Lake Mason	2.2	151	0.07	0.4
Loch Katrine	Lake Mason	1.9	153	0.08	0.4
Lake Aviemore	Lake Benmore	0.2	93	0.40	31
Lake Roxburgh	Speargrass Creek	7.3	514	0.07	0.5
Lake Roxburgh	Butchers Dam	1.5	159	0.11	0.2
Karapiro	Arapuni	0.1	58	0.43	2.1

On consideration of the Type 1 PHES schemes identified, a number of potential barriers to their development become apparent. Lake Aviemore / Lake Benmore and Karapiro / Arapuni use dams on rivers that have cascade hydro power schemes and would need to integrate with the existing power scheme operation. Lake Mason, Lake Luna and Lagoon Creek are remote from the grid or difficult to access. Butchers Dam and Lake Dispute are in recreational reserves. This leaves Lake Johnson and Speargrass Creek as candidates for further consideration.

Lake Johnson lies above Lake Wakatipu, near Queenstown, close to the Frankton GXP. Load growth in Queenstown has been significant in recent years with a winter peak of 67 MW which is expected to rise to 76MW by 2023 [39]. It is expected that Distributed Generation will be required from winter from 2019 to ensure N-1 transmission security [40], hence there will be local benefit to installing generation here. Potential barriers to a Lake Johnson scheme are the visual amenity of the Wakatipu basin and proximity to Frankton which is a large residential area; an underground power house could mitigate these barriers.

Speargrass Creek lies above Lake Roxburgh, which is on the Clutha River, but closer than Lake Onslow. The Speargrass Creek water body is formed by a small dam which could be raised to greatly increase the storage capacity. The storage capacities of the schemes identified here uses properties of water bodies as they exist in the NZ Lakes database, and it would be necessary to modify the water bodies to enable a workable operating range. Allowing modification of the water bodies widens the suitability criteria and a more sophisticated search method as demonstrated by Rogeau et al. should be applied [24].

While the search of existing water bodies highlights few possibilities, the number of potential schemes of Types 2 through 4 is far greater. Searching for schemes of Types 2 through 4 is a complex task with engineering optimisation, GIS and location specific knowledge useful.

Type 2 schemes

While Roxburgh-Speargrass Creek is identified as a candidate for a Type 1 scheme, it also appears in the ANU PHES atlas [29] as a Type 2 scheme with a storage capacity of 15 GWh. Lake Roxburgh is also proposed as a common lower reservoir for the Lake Onslow scheme. This begs the question - what is the best Type 2 scheme using Lake Roxburgh?

Table 4 Possible PHES scheme details

Type	Name	Head [m]	Distance [km]	H/L	Capacity [MW]	Storage [GWh]
1	Speargrass Creek	514	7.3	0.07	200	1.4
2	Onslow	650	20.0	0.03		12000
3	Irrigation pond	264	0.8	0.35	200	0.05
4	ANU	515	7.0	0.07	330	15
2	Fruitlands	264	1.7	0.15	200	8.2
3	Dairy Creek	75	1.1	0.07	0.3	0.02
3	Hakataramea	145	1.0	0.15	2	0.07
3	Macraes	200	0.3	0.61		0.5
4	Ruakawa (best guess)	180	1.5	0.12	200	0.25
4	Ruakawa – (quasi-optimal)	205	1.7	0.12	200	1.5

A model has been built to efficiently calculate the cost-benefit of a Type 2 scheme by defining a rectangle on a contour map derived from a 15m DEM [41]. The rectangle is defined using an easting, northing, flooded depth, radius, stretch, and azimuth. Using the rectangle to represent the crest of a dam or dykes; the flooded volume, dam volume and height, penstock length and width, and powerhouse size are calculated. Costs are attributed to each element and a cost-benefit value found, assuming the benefit is proportional to the logarithm of the energy stored to capacity ratio. The cost-benefit model is used to support an evolutionary algorithm which is applied to find a quasi-optimal location for an upper reservoir near Lake Roxburgh[1]. The solution indicates a reservoir constructed at Fruitlands would yield a scheme with a head to length ratio double that for Speargrass Creek as detailed in Table 4.

[1] Details of the model will be published in a separate paper at a later date.

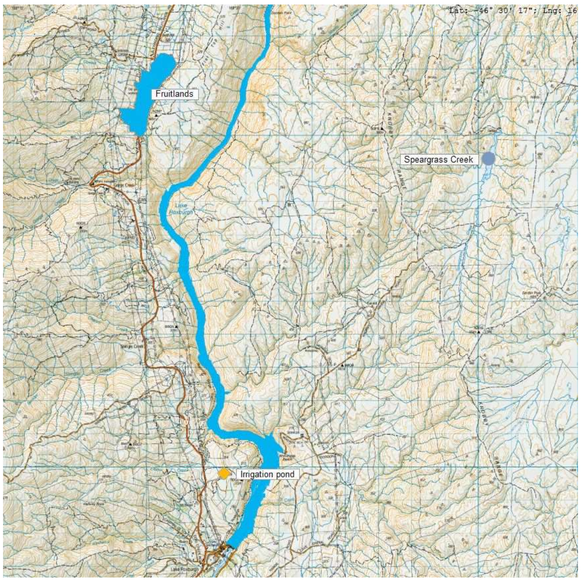

Figure 2 Locations of the Speargrass Creek, Irrigation pond and Fruitland PHES schemes that all use Lake Roxburgh as a lower reservoir

Type 3 schemes

Type 3 schemes use existing assets such as quarry pits and are commonly known as brownfields developments. The identification of these scheme largely relies on location specific knowledge. An irrigation pond has been identified above Lake Roxburgh which could be utilised as an upper reservoir although its present capacity would be limited. Two further candidates highlighted in Table 4 are high head irrigation schemes where the economics could be improved through synergistic operation (the demand for irrigation is present in summer whereas the demand for energy storage is greater during winter). The Dairy Creek scheme draws water from Lake Dunstan (20 km upriver from Roxburgh) to a storage pond, and the Hakataramea scheme draws water from the Waitaki (3 km downstream of the Waitaki Dam). The Macraes mine could be developed on cessation of mining operations; flooding the main pit to the 300m contour and using a 10m working depth accompanied by a pond at the pit crest would allow a 200m head and approximately 0.5 GWh storage.

Type 4 schemes

The evolutionary algorithm used to identify the quasi-optimal Type 2 scheme for Roxburgh is adapted to optimise locations for upper and lower reservoirs simultaneously. This increases the dimensionality and thus the problem space is increased greatly; so a small area of the Ruakawa Range, in Southern Hawkes Bay, is used to demonstrate the algorithm. Initially the space as indicated in Figure 3 was scanned manually and a pair of reservoirs picked to constitute a "best guess". The evolutionary algorithm was then run with initialisation pairs scattered across the entire map and these converged to the quasi-optimal solution as shown in Table 4.

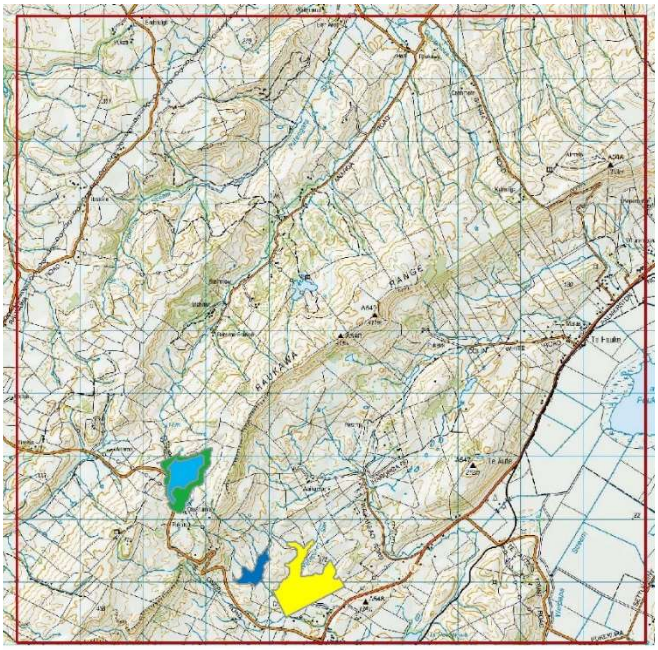

Figure 3 Results of particle swarm optimisation for Ruakawa Range. The dark blue patch represents the "best guess" lower reservoir, and the cyan patch its upper pairing. The yellow patch represents the quasi-optimal lower reservoir and the green/cyan patch its upper pairing. The brown rectangle shows the search space.

Conclusion

Achieving the carbon zero target will require the addition of generation and storage into the New Zealand power system if current levels of security of supply and to be maintained. The most economic, efficient, and lowest emissions technology for large-scale active energy storage is PHES. The economics of PHES are dependent on the geomorphology of the scheme and New Zealand should have an abundance of suitable sites. Few suitable schemes have been previously suggested for New Zealand hence an evaluation of resources is undertaken. A search of existing water body pairs (Type 1) highlights a few possibilities which are used to explore potential barriers to development. Lake Roxburgh, identified as a lower reservoir for a Type 1 scheme using Speargrass Creek as an upper reservoir, is the lower reservoir for the Lake Onslow scheme; this drives the development of an evolutionary algorithm which is applied to find a quasi-optimal upper reservoir for a Type 2 scheme using Lake Roxburgh. The identification of Type 3 schemes relies on location specific knowledge and in New Zealand's case may benefit from synergies with high head irrigation schemes. The scope for development of Type 4 schemes, which use new upper and lower reservoirs, is very large and the evolutionary algorithm is extended and demonstrated with application to a small problem.

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